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From: Timothy M. Sivavec

SUBJECT: PATENT DISCLOSURE LETTER
Remote Monitoring System for Permeable Reactive Barriers

1. OBJECT OF INVENTION

The invention relates to a remote monitoring, diagnostic, and reporting method and system that is designed to monitor the performance of permeable reactive barriers (PRBs). One of the most promising groundwater restoration technologies developed over the last few years has been the use of permeable reactive barriers filled with reactive materials to intercept and destroy contaminant plumes in the subsurface (1-14). Reactive material such as recycled cast iron (zero-valent iron) is placed into the subsurface to intercept a plume of contaminated groundwater which passes through the reactive material under its natural gradient, thereby creating a passive treatment system. As the contaminant passes through the granular iron material, the contaminants are adsorbed to the iron and are reduced to nontoxic end products. A wide variety of chlorinated hydrocarbons, including chlorinated ethenes such as trichloroethene (TCE) and tetrachloroethene (PCE), are effectively treated by this method, often at a significant cost savings when compared to conventional pump-and-treat alternatives. A significant number of toxic metals are also effectively treated using PRB technology (15).

Compliance monitoring of PRBs typically involves the monitoring of contaminants of interest at locations where dissolved concentrations have been detected and exceed regulatory limits. General water quality monitoring is also often included, such as the measurement of major cations and anions, alkalinity, and other water quality indicator parameters such as pH, dissolved oxygen, specific conductance, and oxidation-reduction potential.

Well placement and design are important to ensure adequate assessment of system performance. In addition to placing wells upgradient and downgradient of the PRB, wells are often also located to ensure that contaminated water is not flowing around, under, or over the barrier wall. The number of wells used will depend on the design and size of the PRB. Wells of 2 inch diameter or even smaller (*e.g.*, $\frac{3}{4}$ inch inner diameter) are usually appropriate for compliance monitoring purposes. Low-flow sampling methods are typically used for compliance sampling purposes (16). Low-flow refers to the velocity with which water is withdrawn with a pump from the aquifer and is usually from 0.1 to 0.5 L/min, depending on site-specific hydrogeologic conditions. The objective is to pump groundwater to the surface for measurement and sample collection in a manner that minimizes stress to the hydrogeologic system. However, the action of pumping groundwater to the surface for measurement in an in-line flow cell often introduces atmospheric gases into the sampled groundwater. This is next to impossible to control. The use of in-well field indicator probes as disclosed in this letter avoids this source of error, in that the measurement is made in the well water directly.

Monitoring within the PRB itself poses a number of unique challenges. Low-purge methods are often inappropriate because the withdrawal of large volumes of water may compromise PRB sampling objectives. Data is often sought to confirm degradation rates that were used to design the PRB or to assess changes in iron media reactivity. These rates and changes may need to be addressed over relatively small spatial intervals. To do this accurately, water from much smaller volumes of the aquifer and within the PRB must be withdrawn. This is where the use of passive or semi-passive sampling approaches can provide advantages over conventional low-purge sampling methods. Several researchers have shown that discrete-level sampling approaches may be used to provide no-purge samples representative of formation water (17-20). A number of automated and manual groundwater monitoring systems have been patented in recent years, most of them requiring the use of pumps to withdraw groundwater to the surface for sampling and/or monitoring (21-24). Several others use devices to monitor groundwater characteristic in general aquifer environments (24-25). This letter shows that such a monitoring system can be used to monitor the performance of a PRB under a geochemical environment quite different from that of an aquifer or landfill.

Water quality indicator parameters are often used to determine purging needs prior to sample collection in each well. Stabilization of parameters such as pH, specific conductance, dissolved oxygen, oxidation-reduction potential, temperature and turbidity is used to determine when formation water (as opposed to well or borehole water) is accessed during purging. Most of these same parameters are important performance indicators for PRBs composed of granular iron. Many of these parameters are important as indicators of the corrosion process for iron-mediated transformations within the iron PRB. For example, it is common to measure significantly reduced specific conductivities within the iron media relative to up- and downgradient monitoring points. Significantly higher pH values are also measured within the iron PRB relative to monitoring points elsewhere in the aquifer. PH values of between 9 and 11 are commonly observed, as compared to near neutral pH (ph 7) elsewhere in the aquifer. Similarly, oxidation-reduction values are significantly lower measured in a well location within an iron PRB as compared to up- or downgradient of the PRB.

This invention then addresses the need to measure important field indicator parameters (sometimes called groundwater quality parameters) using a passive technique that does not require the retrieval of formation water by use of a pump. This method provides a method to gain such data in near, real-time and to access such data remotely.

2. DESCRIPTION OF INVENTION

The invention provides a remote monitoring, diagnostics, and reporting system and method for monitoring the performance of a permeable reactive barrier (PRB). The invention provides real-time and historic data and increased data density relative to conventional low-flow sampling of formation water to improve understanding of processes occurring in and around PRBs. The monitoring system can be used to determine groundwater characteristics such as pH, dissolved oxygen, specific conductance, and oxidation-reduction potential. These field indicator parameters are particularly useful in assessing the performance of an iron PRB, as they are much changed in the presence of zero-valent iron owing to the corrosion reaction between iron and water under reducing conditions.

For example, within a 100% iron PRB, pH is typically increased from neutral to a value between 9 and 11. Dissolved oxygen will also be reduced in the presence of zero-valent iron. As most PRBs are emplaced in anaerobic aquifers where no significant dissolved oxygen is found, this is not usually very important in evaluating performance of a PRB. However, if water is being treated above-ground, dissolved oxygen is commonly introduced into the pumped groundwater and can result in clogging or cementation of the iron at the entrance to the iron system. Hence, monitoring for dissolved oxygen in above-ground applications can be useful in sustaining performance over the long term. Specific conductance of a groundwater sample is often reduced significantly (e.g., by 50% or more) in the presence of 100% iron. Oxidation-reduction potential is also a direct measure of the reducing environment of the iron media. It often measures less than -400 mV.

The monitoring system comprises an in-well module containing at least one sensor. The module may include any number of sensors that may be used to monitor groundwater characteristics. The module is placed down a groundwater well, typically at the mid-point of the screened interval. Groundwater wells include, but are not limited to, private and municipal drinking water wells, pollution control wells, and landfill monitoring wells. The wells can be spread throughout a remediation site to also provide data on groundwater elevation and gradients. The module includes a communications unit, which is electronically coupled to the module and is capable of transmitting data to a data collection center. The signals may be communicated, for example, from a well transceiver to the data collection system by at least one hardwired communication connection, such as, but not limited to, an electrical conductor, wireless communication connections, such as, but not limited to, radio signals, satellite communications and combinations of wireless and hardwired connections. The communications unit also typically comprises an antenna that is connected to the transceiver, unless the communications unit is hardwired.

The data collection center comprises a center communications unit that is capable of receiving signals from the transceiver and a control that analyzes the signals and generates information on groundwater characteristics. The control of the data collection system typically includes a "user friendly" data acquisition software package that transforms information into easy-to-read formats.

The information transmitted to the data collection center contains data representative of groundwater characteristics important to monitoring PRB performance. The report format provides real-time information and historical trend analysis of groundwater within and around a PRB installation. The real-time information permits a quicker response to undesirable groundwater characteristics, such as a rise in groundwater elevation caused by changes in the hydraulic conductivity of the PRB. It also provides trend analysis of oxidation-reduction potential, pH, specific conductivity, all indicative of an active corrosion environment within an iron PRB.

The monitoring system typically reduces monitoring and reporting costs at a PRB remediation site and provides enhances, readily available data more frequently than conventional monitoring systems that require one or more operators actively purging a number of wells at a given site. It also removes an important source of error in oxidation-reduction potential and dissolved oxygen measurements. That source of error is the introduction of atmospheric gases into the withdrawn groundwater leading to inaccurate measurements. The magnitude of such effects is shown in the reduction to practice data, where the low-flow purge method is compared directly with the in-well monitoring system at the same wells over an extended period.

3. REDUCTION TO PRACTICE

The invention has been fully reduced to practice in the field at Somersworth Sanitary Landfill Superfund Site, Somersworth, NH. An extended field test was performed evaluating the long-term performance of a constructability PRB test cell containing 100% granular iron. Four well modules were deployed in 4 well location, one upgradient of the iron zone, two within the iron zone, and one downgradient of the iron zone (see attached Figure). The four well location were along a transect in the direction of groundwater flow at the site. Table 1 compares temperature, pH, specific conductivity, dissolved oxygen, and oxidation-reduction potential measured by the in-well monitoring system and the conventional low-flow purge method. The high dissolved (DO) values and the more positive oxidation-reduction potential (ORP) values measured by the low-flow purge method are clearly in error, as a groundwater cannot be highly reducing (<-100 mv ORP) and contain such high concentrations of dissolved oxygen (~3.5 mg/L). This type of data is not uncommon when low-flow purge methods are used.

4. RECORDS

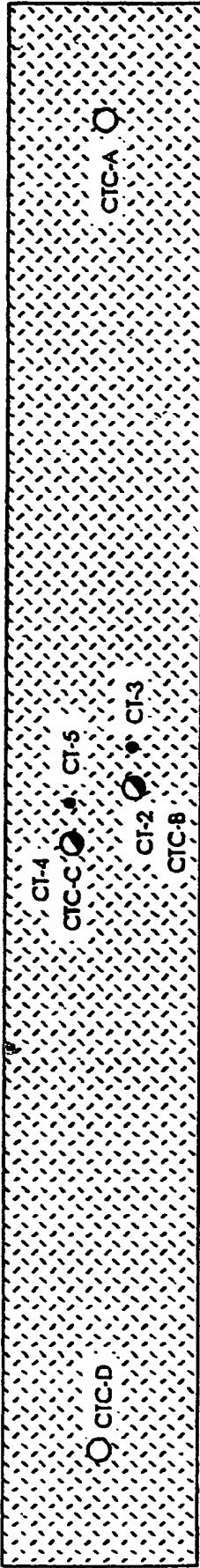
This invention and its reduction to practice are disclosed in Notebook C-243 assigned to T.M. Sivavec.

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DRAFT

● CT-6



Inferred direction of
groundwater flow

- 3/4" monitoring well
- core sample location
- 2" monitoring well
- core sample location
- chemical treatment wall test section



Locations of Core Samples and Monitoring Wells
for the Biosurry Constructability Test
Somersworth Landfill Superfund Site, Somersworth, NH

Figure: 3

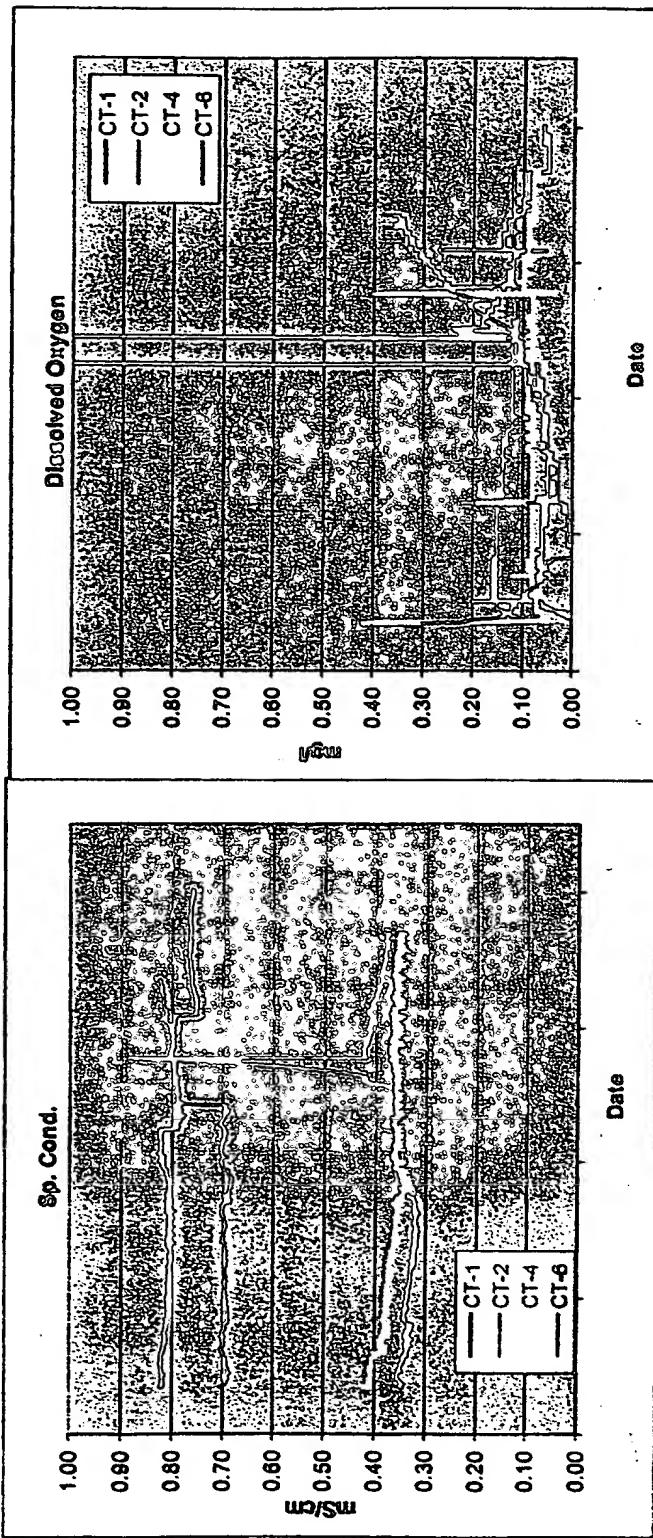
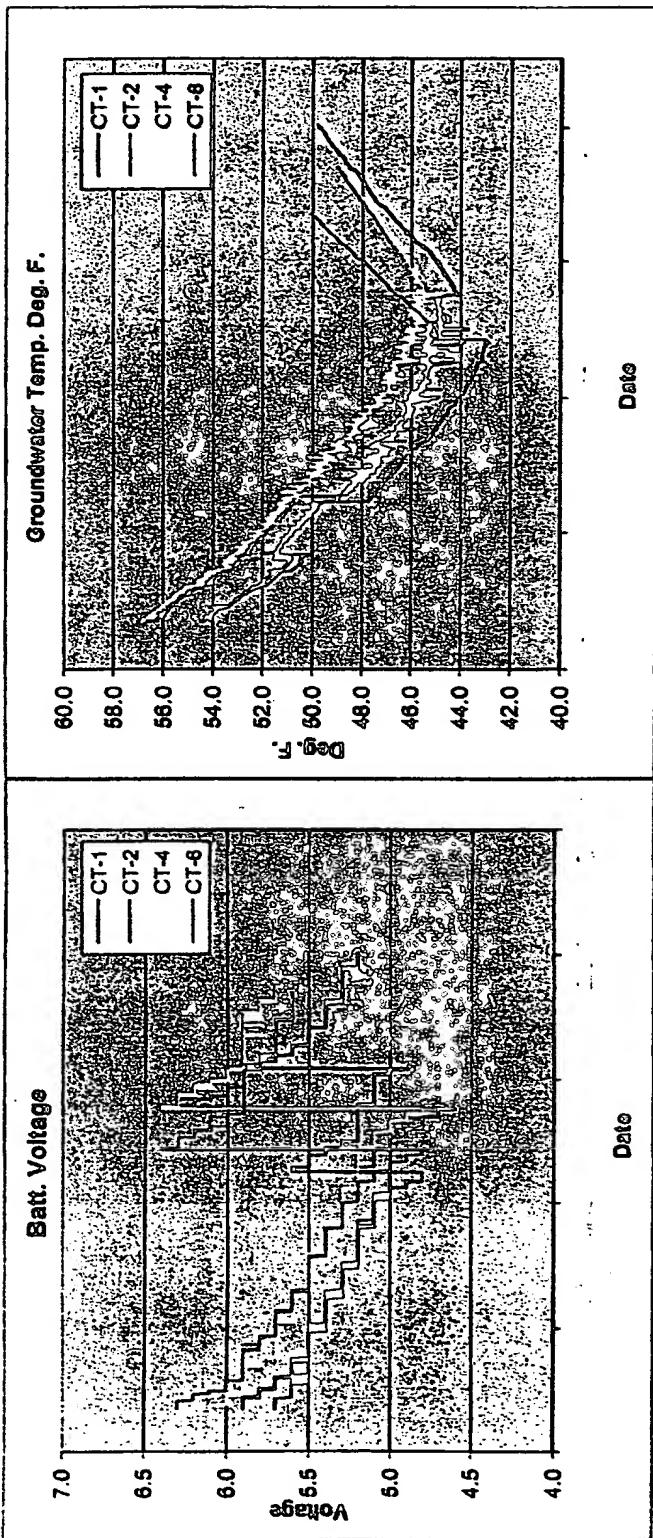
GeoSYNTEC
Consultants

FIELD DATA COMPARISON FROM SOMERSWORTH NH SITE

LOOKING AT LOW-PURGE DATA COMPARED TO INSITU DATA

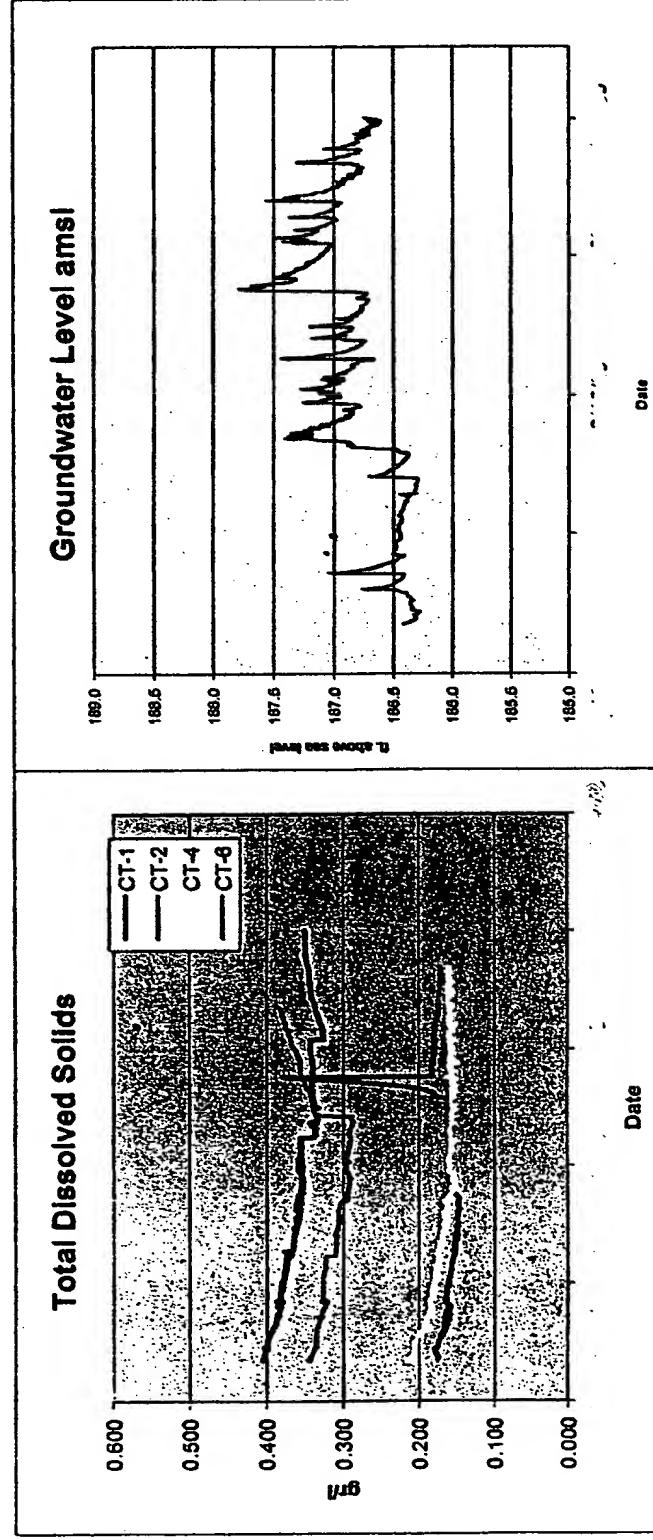
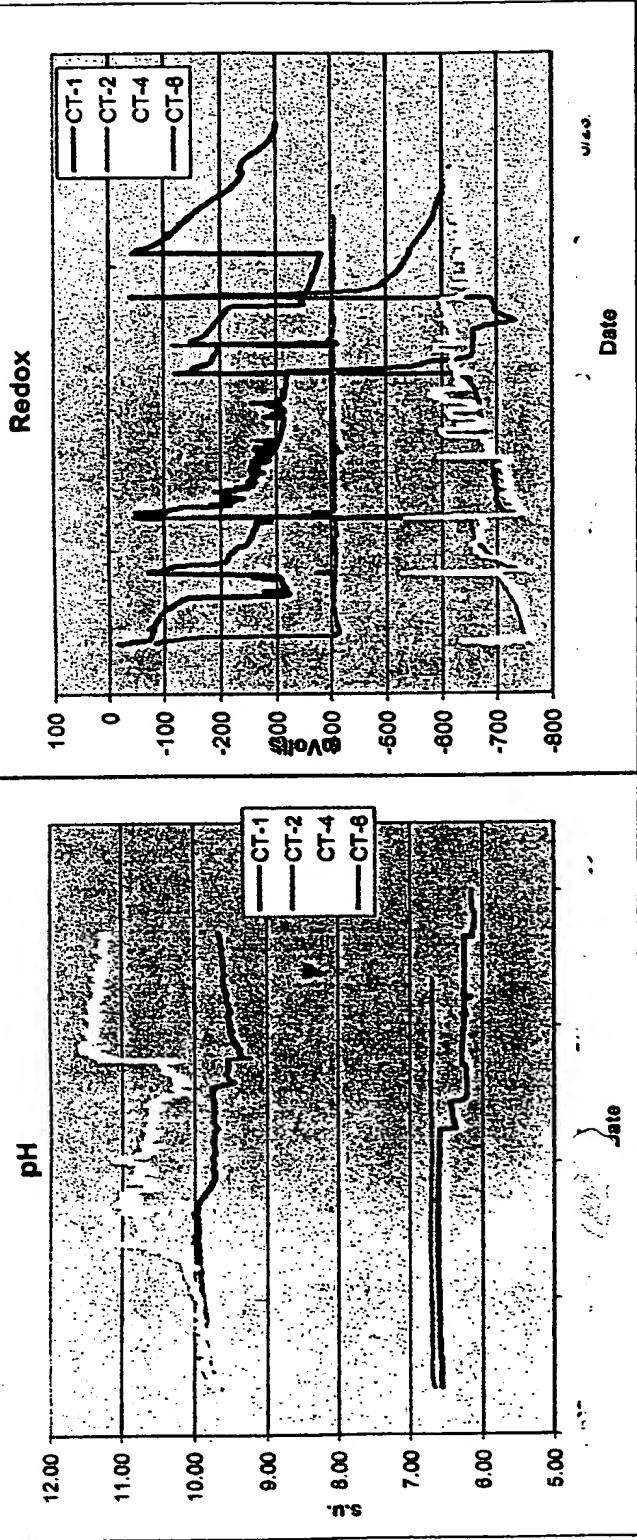
WELL	DATE	Method	TEMP Deg. C.	pH s.u.	SpCond uS/cm	DO mg/l	ORP mV
CT-1	@13:30	Purge	11.35	6.21	810	3.54	-121
		Insitu	11.94	6.57	816	0.05	-71
	@10:55	Purge	9.40	6.46	793	0.79	-145
	@10:30	Insitu	11.10	6.59	811	0.06	-90
		Purge	9.30	6.40	821	3.50	-160
		Insitu	10.47	6.61	806	0.06	-93
CT-6	@14:00	Purge	11.05	6.31	837	1.55	-147
		Insitu	12.13	6.69	685	0.12	-413
	@09:40	Purge	8.73	6.56	820	0.65	-205
		Insitu	10.89	6.70	692	0.03	-392
	@10:45	Purge	8.40	6.50	851	2.50	-185
		Insitu	8.59	6.70	694	0.04	-369
CT-3		Purge	10.90	8.50	461	0.65	-578
CT-2	@10:00	Insitu	13.19	9.71	356	0.15	-744
CT-3		Purge	8.78	8.57	504	0.78	-441
CT-2	@13:00	Insitu	11.45	9.83	343	0.15	-737
CT-3		Purge	9.60	9.00	524	3.30	-457
CT-2	@12:30	Insitu	10.29	9.93	330	0.14	-710
CT-5		Purge	10.89	9.18	427	0.45	-676
CT-4	@11:00	Insitu	13.36	9.70	409	0.06	-752
CT-5		Purge	7.24	9.73	438	0.71	-410
CT-4	@13:40	Insitu	11.69	9.90	382	0.08	-696
CT-5		Purge	9.60	9.70	469	2.60	-522
CT-4	@12:50	Insitu	10.47	10.10	373	0.08	-739

IN SITU PROBE DATA
Somersworth Sanitary Landfill Superfund Site, NH



Somersworth YSI Data

IN SITU PROBE DATA
Somersworth Sanitary Landfill Superfund Site, NH



Somersworth YSI Data

Sonde Summary for Date

Summary Sheet of Sonde data

CT-1

Date/Time MM/DD	Category	V	T	P	Depth ft	Depth Corrected	Latitude mSkm	Longitude deg	DO ppm	DO mg/L	pH	Temp deg	Temp K
	Average	5.7	52.48	15.013	186.623	0.817	0.05	0.5	6.58	-159	0.393		
	max	5.9	54.45	15.607	187.217	0.823	0.20	1.8	6.59	-15	0.406		
	min	5.5	50.79	14.833	186.443	0.809	-0.05	-0.5	6.56	-324	0.381		
	Average	5.4	50.64	16.610	188.220	0.807	0.06	0.5	6.60	-222	0.378		
	max	5.5	51.99	16.689	188.299	0.811	0.07	0.6	6.61	-73	0.387		
	min	5.4	49.61	14.976	186.586	0.804	0.05	0.5	6.59	-294	0.371		
	Average	5.2	46.83	15.304	186.914	0.810	0.06	0.5	6.61	-268	0.358		
	max	5.4	50.84	16.380	187.990	0.827	0.17	1.5	6.63	-45	0.378		
	min	5.0	44.81	14.172	185.782	0.796	0.04	0.3	6.58	-321	0.352		
	Average	5.2	44.71	15.450	187.060	0.794	0.15	1.2	6.29	-263	0.339		
	max	5.6	45.52	16.180	187.790	0.802	0.24	1.9	6.44	-121	0.344		
	min	5.0	43.68	15.098	186.708	0.777	0.11	0.9	6.21	-383	0.332		
	Average	5.2	44.72	15.452	187.062	0.794	0.15	1.2	6.29	-264	0.339		
	max	5.9	45.52	16.180	187.790	0.802	0.26	2.2	6.44	-43	0.344		
	min	4.9	43.68	15.098	186.708	0.752	0.06	0.5	6.21	-383	0.325		
Total	Average	5.3	47.73	15.485	187.095	0.806	2.15	17.8	6.50	-241	0.361		
	max	5.9	54.45	16.689	188.299	0.827	30.72	254.1	6.63	-15	0.406		
	min	5.0	43.68	14.172	185.782	0.777	-0.05	-0.5	6.21	-383	0.332		

CT-2

Date/Time MM/DD	Category	V	T	P	Depth ft	Depth Corrected	Latitude mSkm	Longitude deg	DO ppm	DO mg/L	pH	Temp deg	Temp K
	Average	5.6	54.61	14.961	186.581	0.341	0.14	1.4	9.83	-732	0.169		
	max	5.7	56.61	15.536	187.156	0.356	0.20	1.9	9.94	-701	0.180		
	min	5.5	52.87	14.822	186.442	0.325	0.07	0.7	9.64	-752	0.157		
	Average	5.4	51.73	14.923	186.543	0.336	0.15	1.4	9.89	-677	0.160		
	max	5.5	52.68	14.989	186.609	0.344	0.15	1.4	9.93	-649	0.166		
	min	5.4	50.68	14.871	186.491	0.326	0.15	1.3	9.83	-737	0.154		
	Average	5.2	48.58	14.693	186.313	0.339	0.13	1.1	9.86	-678	0.154		
	max	5.4	51.07	16.221	187.841	0.364	0.22	2.0	10.03	-403	0.161		
	min	4.8	46.27	12.806	184.426	0.314	0.11	1.0	9.71	-716	0.144		
	Average	4.9	45.15	15.646	187.266	0.430	0.12	1.0	9.66	-643	0.185		
	max	5.2	45.95	16.350	187.970	0.881	0.13	1.1	9.77	-256	0.379		
	min	4.6	44.40	15.285	186.905	0.357	0.11	0.9	9.44	-733	0.155		
	Average	5.8	45.81	15.267	186.887	0.404	0.12	1.0	9.69	-644	0.175		
	max	6.3	47.69	16.350	187.970	0.881	0.27	2.2	9.77	-40	0.379		
	min	5.6	44.40	12.806	184.426	0.351	0.11	0.9	9.22	-733	0.155		
Total	Average	5.4	48.89	15.130	186.750	0.370	0.13	1.2	9.74	-644	0.168		
	max	6.3	56.61	16.350	187.970	0.881	0.31	2.6	10.03	-40	0.379		
	min	4.6	44.40	12.806	184.426	0.314	0.07	0.7	9.22	-752	0.144		

GUNNISON RIVER DATA

CT-4

Date/Time M.D.Y.	Battery V	Temp F	Depth ft	Depths Corrected m/s/cm	Flow rate m³/sec	Flow rate cfs	Disch. ft²	Disch. cfs	Q/F ft²/cfs	Q/F m²/m³/s
5/5/02 Average	5.9	54.97	14.751	186.521	0.397	0.08	0.8	9.85	-733	0.198
max	6.1	56.87	15.331	187.101	0.422	0.42	4.0	9.98	-631	0.216
min	5.7	53.02	14.612	186.382	0.378	0.05	0.5	9.67	-759	0.184
5/6/02 Average	5.7	52.02	14.680	186.450	0.377	0.08	0.7	9.99	-680	0.180
max	5.7	53.11	14.745	186.515	0.384	0.08	0.8	10.13	-526	0.186
min	5.6	50.96	14.632	186.402	0.370	0.08	0.7	9.87	-753	0.175
5/7/02 Average	5.4	48.59	15.049	186.819	0.358	0.08	0.7	10.70	-672	0.163
max	5.6	51.25	15.689	187.459	0.374	0.19	1.7	11.14	-532	0.176
min	5.2	46.45	14.159	185.929	0.337	0.08	0.7	9.95	-748	0.152
5/8/02 Average	5.1	45.94	15.232	187.002	0.360	0.08	0.7	10.43	-612	0.157
max	5.2	46.71	16.067	187.837	0.367	0.09	0.7	10.71	-587	0.160
min	4.8	44.69	15.030	186.800	0.353	0.08	0.7	10.09	-653	0.154
5/9/02 Average	6.0	47.08	15.264	187.034	0.359	0.09	0.8	11.33	-622	0.159
max	6.4	48.84	15.838	187.608	0.371	0.40	3.4	11.59	-331	0.165
min	5.7	45.49	14.900	186.670	0.348	0.04	0.3	10.38	-661	0.152
Total Average	5.6	49.08	15.051	186.821	0.366	0.08	0.7	10.63	-659	0.168
max	6.4	56.87	16.067	187.837	0.422	0.42	4.0	11.59	-331	0.216
min	4.8	44.69	14.159	185.929	0.337	0.04	0.3	9.67	-759	0.152

CT-6

Date/Time M.D.Y.	Battery V	Temp F	Depth ft	Depths Corrected m/s/cm	Flow rate m³/sec	Flow rate cfs	Disch. ft²	Disch. cfs	Q/F ft²/cfs	Q/F m²/m³/s
5/5/02 Average	6.0	52.26	14.579	186.459	0.696	0.09	0.9	6.69	-378	0.334
max	6.3	54.31	15.167	187.047	0.705	0.30	2.8	6.71	-84	0.347
min	5.8	50.39	14.401	186.281	0.685	0.04	0.4	6.66	-414	0.322
5/6/02 Average	5.7	50.72	18.527	190.407	0.694	0.01	0.1	6.71	-407	0.325
max	5.9	51.60	18.646	190.526	0.697	0.02	0.2	6.71	-372	0.329
min	5.6	49.85	14.528	186.408	0.689	-0.06	-0.5	6.70	-411	0.320
5/7/02 Average	5.4	45.34	14.897	186.777	0.695	0.06	0.5	6.71	-402	0.300
max	5.6	47.79	15.580	187.460	0.704	0.10	0.8	6.73	-104	0.312
min	5.1	43.33	13.862	185.742	0.682	0.03	0.2	6.69	-420	0.290
5/8/02 Average	4.9	43.07	15.141	186.911	0.697	0.10	0.8	6.70	-404	0.290
max	5.1	43.32	15.659	187.429	0.706	0.11	0.9	6.71	-403	0.294
min	4.8	42.87	14.640	186.410	0.688	0.09	0.8	6.69	-405	0.286
5/9/02 Average	5.9	47.35	15.066	186.836	0.804	0.26	2.2	6.70	-396	0.358
max	6.4	50.04	16.232	188.002	0.824	0.50	4.1	6.72	-91	0.383
min	5.7	44.56	13.422	185.192	0.786	0.10	0.8	6.67	-407	0.335
Total Average	5.7	47.64	15.386	187.226	0.729	0.12	1.0	6.70	-397	0.326
max	6.4	54.31	18.646	190.526	0.824	0.50	4.1	6.73	-84	0.383
min	4.8	42.87	13.422	185.192	0.682	-0.06	-0.5	6.66	-420	0.286

Survey Point	FS	BS	Elevation	DTW	2/12/Elev	
FS-11 PVC		4.99	192.47			Notes:
FS-13 PVC		5.29	192.14			PVC = top of PVC well casing
TW-1 PVC	5.8		191.65			TOC = top of protective (outer) casing
TW-1 TOC	5.26		192.19	6.12	186.1	GRND = ground elevation
TW-1 GRND	7.86		189.59			
TW-2 PVC	5.77		191.68			
TW-2 TOC	5.02		192.43	5.91	186.5	
TW-2 GRND	7.77		189.68			
TW-3 PVC	5.94		191.51			
TW-3 TOC	5.03		192.42	5.90	186.5	
TW-3 GRND	7.96		189.49			
TW-4 PVC	5.47		191.98			
TW-4 TOC	4.95		192.50	5.64	186.9	
TW-4 GRND	7.66		189.79			
CT-1 PVC	3.34		194.11			
CT-1 TOC	2.86		194.59	8.21	186.4	
CT-1 GRND	5.27		192.18			
CT-2 PVC	3.33		194.12			
CT-2 TOC	2.7		194.75	8.40	186.3	
CT-2 GRND	5.23		192.22			
CT-3 PVC	4.18		193.27			
CT-3 TOC	3.56		193.89			
CT-3 GRND	5.31		192.14			
CT-4 PVC	3.18		194.27			
CT-4 TOC	2.68		194.77	8.43	186.3	
CT-4 GRND	5.19		192.26			
CT-5 PVC	3.66		193.79			
CT-5 TOC	3.5		193.95			
CT-5 GRND	5.29		192.16			
CT-6 PVC	3.07		194.38			
CT-6 TOC	2.63		194.82	8.50	186.3	
CT-6 GRND	5.15		192.30			

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